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ME469: Geometric Fidelity

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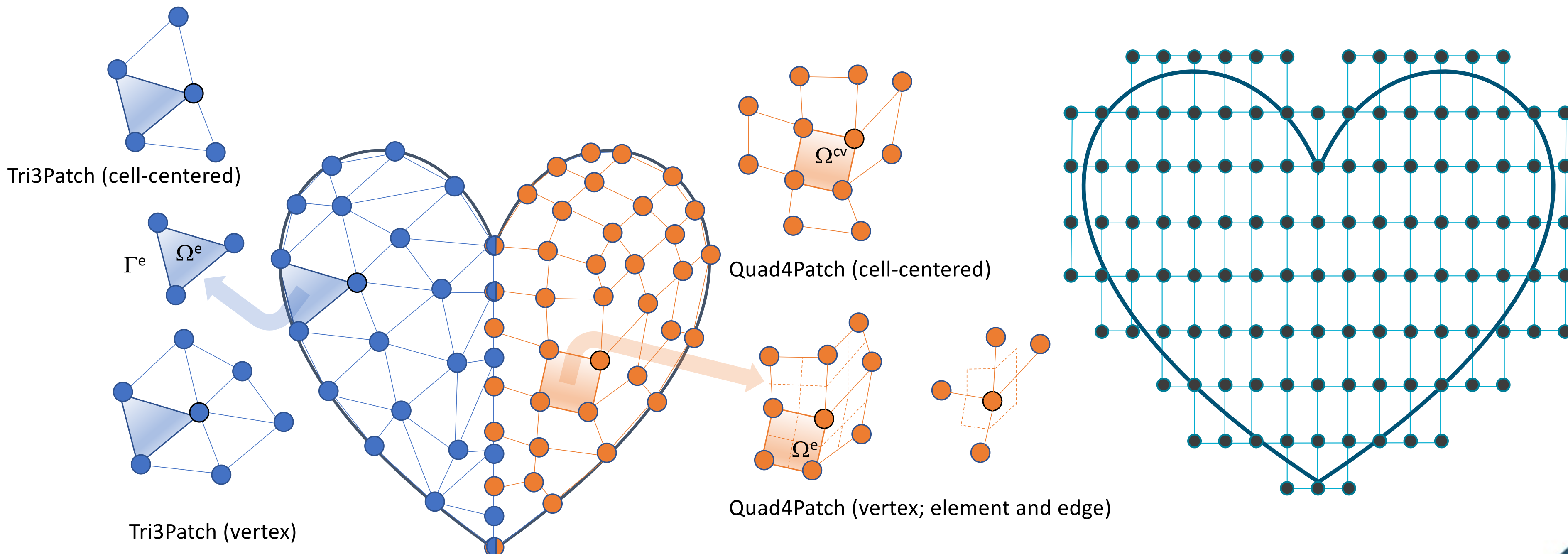
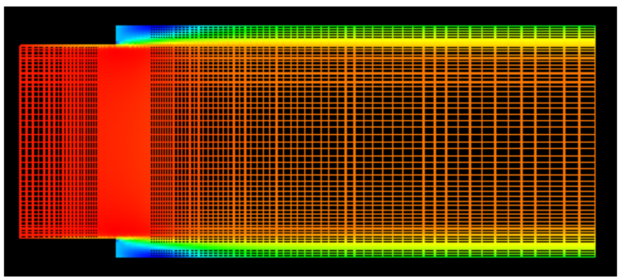
Review of Discretization Options

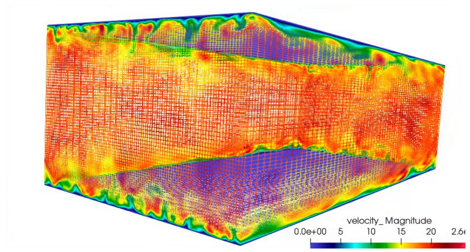
- Degree-of-freedom (DOF) for:
  - Cell-centered: Stencil is based on an element:face:element
  - DOFs at vertices of elements, or “nodes”, element:node (CVFEM, FEM), edge:node (EBVC)

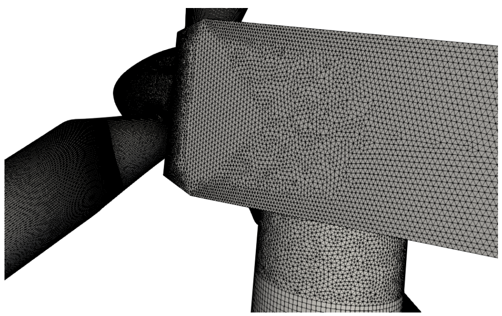


Simple vs Complex Domains

- Some Geometries are simple, while others are complex







Review: Simple One-Dimensional Diffusion MMS Example

Let us introduce (briefly) the Method of Manufactured Solutions (MMS)

- Consider a simple diffusion equation:

$$\frac{d^2\phi}{dx^2} = 0$$

with a presumed, or manufactured solution: $\phi^{MMS}(x) = x^2$

$$\frac{d^2\phi^{MMS}}{dx^2} = S^{MMS} = 2$$

Gauss-Divergence

$$\int \frac{d^2\phi^h}{dx^2} dV = \int S^{MMS} dV \qquad \int \frac{d\phi^h}{dx} dS = \int S^{MMS} dV$$

Discrete flux-based form at the sub-control volume surface (scs) and sub-control volume IP:

$$\sum_{scsIP} \frac{d\phi^h}{dx} A_{scsIP} = \sum_{scvIP} S^{MMS} V_{scvIP}$$

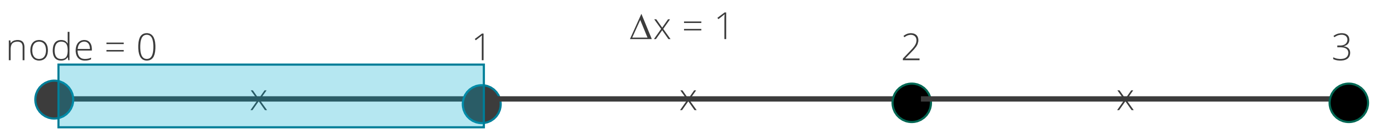
With error: $\epsilon = \phi^{MMS} - \phi^h$

First….

- Let’s review matrix assembly from a previous lecture, with a focus on a verification “patch test”
- Recall, a linear basis was able to reconstruct a quadratic solution perfectly when the norm was computed at the degree of freedom locations

Simple One-D MMS Example; Edge-based Assemble of Diffusion

We will use a linear basis and solve this system over a small patch of linear bar elements



Recall, simplified equation with RHS from source term already provided

$$\sum_{scsIP} \frac{d\phi^h}{dx}_{scsIP} = \sum_{scvIP} S^{MMS} \frac{\Delta x}{2}$$

Iterate elements with a simple left-hand side rule: += L and -=R

(note implicit conservation statement)

$$LHS_0 += \frac{\phi_1^h - \phi_0^h}{\Delta x}$$

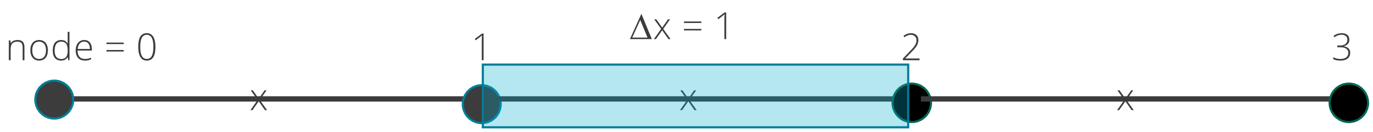
$$LHS_1 -= \frac{\phi_1^h - \phi_0^h}{\Delta x}$$

Edge 1

$$\frac{d\phi^h}{dx}_{scsIP} = \frac{\phi_1^h - \phi_0^h}{\Delta x} + C_0(\Delta x) + \ldots$$

Simple One-D MMS Example; Edge-based Assemble of Diffusion

We will use a linear basis and solve this system over a small patch of linear bar elements



Recall, simplified equation with RHS from source term already provided

$$\sum_{scsIP} \frac{d\phi^h}{dx}_{scsIP} = \sum_{scvIP} S^{MMS} \frac{\Delta x}{2}$$

Iterate elements with a simple left-hand side rule: += L and -=R

(note implicit conservation statement)

$$\frac{d\phi^h}{dx}_{scsIP} = \frac{\phi_2^h - \phi_1^h}{\Delta x} + C_0(\Delta x) + ...$$

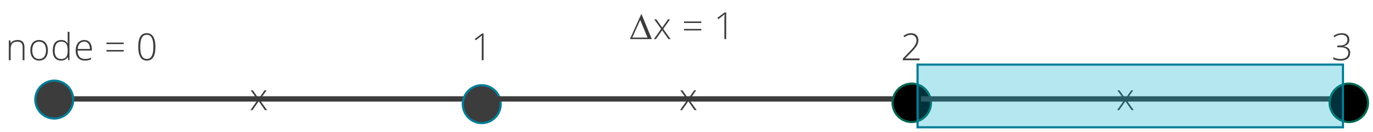
$$LHS_1 + = \frac{\phi_2^h - \phi_1^h}{\Delta x}$$

$$LHS_2 - = \frac{\phi_2^h - \phi_1^h}{\Delta x}$$

Edge 2

Simple One-D MMS Example; Edge-based Assemble of Diffusion

We will use a linear basis and solve this system over a small patch of linear bar elements



Recall, simplified equation with RHS from source term already provided

$$\sum_{scsIP} \frac{d\phi^h}{dx}_{scsIP} = \sum_{scvIP} S^{MMS} \frac{\Delta x}{2}$$

Iterate elements with a simple left-hand side rule: += L and -=R

(note implicit conservation statement)

$$\frac{d\phi^h}{dx}_{scsIP} = \frac{\phi_3^h - \phi_2^h}{\Delta x} + C_0(\Delta x) + \ldots$$

$$LHS_2 + = \frac{\phi_3^h - \phi_2^h}{\Delta x}$$

$$LHS_3 - = \frac{\phi_3^h - \phi_2^h}{\Delta x}$$

Edge 3

Simple One-D MMS Example; Collect all of the terms

$$LHS_0+ = \frac{\phi_1^h - \phi_0^h}{\Delta x}$$

$$LHS_1- = \frac{\phi_1^h - \phi_0^h}{\Delta x}$$

$$LHS_1+ = \frac{\phi_2^h - \phi_1^h}{\Delta x}$$

$$LHS_2- = \frac{\phi_2^h - \phi_1^h}{\Delta x}$$

$$LHS_2+ = \frac{\phi_3^h - \phi_2^h}{\Delta x}$$

$$LHS_3- = \frac{\phi_3^h - \phi_2^h}{\Delta x}$$

$$A = \frac{1}{\Delta x}\begin{bmatrix} -1 & +1 & 0 & 0 \\ +1 & -2 & +1 & 0 \\ 0 & +1 & -2 & 1 \\ 0 & 0 & +1 & -1 \end{bmatrix}$$

Fully assembled matrix

$$\frac{1}{\Delta x}\begin{bmatrix} -1 & +1 & 0 & 0 \\ +1 & -2 & +1 & 0 \\ 0 & +1 & -2 & 1 \\ 0 & 0 & +1 & -1 \end{bmatrix}\begin{bmatrix} \phi_0 \\ \phi_1 \\ \phi_2 \\ \phi_3 \end{bmatrix} = \begin{bmatrix} 2 \\ 2 \\ 2 \\ 2 \end{bmatrix}$$

Fully assembled system

$$\frac{1}{\Delta x}\begin{bmatrix} +1 & 0 & 0 & 0 \\ +1 & -2 & +1 & 0 \\ 0 & +1 & -2 & 1 \\ 0 & 0 & 0 & +1 \end{bmatrix}\begin{bmatrix} \phi_0 \\ \phi_1 \\ \phi_2 \\ \phi_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 2 \\ 2 \\ 9 \end{bmatrix}$$

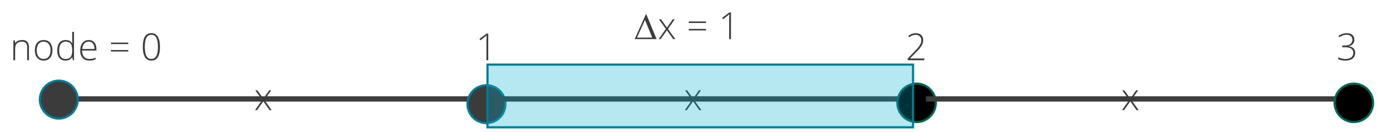
Correct for BCs

$$\phi^h = \begin{bmatrix} 0 \\ 1 \\ 4 \\ 9 \end{bmatrix}$$

Solution is exact..... Linear basis exactly captures a quadratic solution

Simple One-D Advection; Edge-based Assembly

Similar approach: Iteration of edges, definition of Left and Right node, etc.



$$\int w \frac{\partial \rho u_j \phi}{\partial x_j} dV \approx \sum_{ip} \left(\rho u_j\right)_{ip} \phi_{ip} n_j dS \approx \sum_{ip} \dot{m}_{ip} \phi_{ip}$$

$$\dot{m}_{ip} = \rho u_j n_j dS|_{ip} = \rho u_j A_j|_{ip}$$

We may also create a local matrix data structure, A[4]: With:

- A[0] += lhsFac (row node 1, column node 1, “central-coeff”)
- A[1] += lhsFac (row node 1, column node 2, ”east-coeff”)
- A[2] -= lhsFac (row node 2, column node 1, “west-coeff”)
- A[3] -= lhsFac (row node 2, column node 2, “central-coeff”)

$$LHS_1 + = \frac{\dot{m}}{2}\left(\phi_1^h + \phi_2^h\right)$$

$$LHS_2 - = \frac{\dot{m}}{2}\left(\phi_1^h + \phi_2^h\right)$$

With: $lhsFac = \dfrac{\dot{m}}{2}$

Edge 2

Focus on Three Nalu/reg_tests/test_files/laboratory

- 2d_quad9_couette
- 2d_quad4_channel
- 3d_tet4_pipe

Nalu/reg_tests/test_files/laboratory/2d_quad9_couette: Geometry/Boundary Conditions

- Top, imposed velocity
- Bottom, no-slip wall
- Left and right sides, periodic

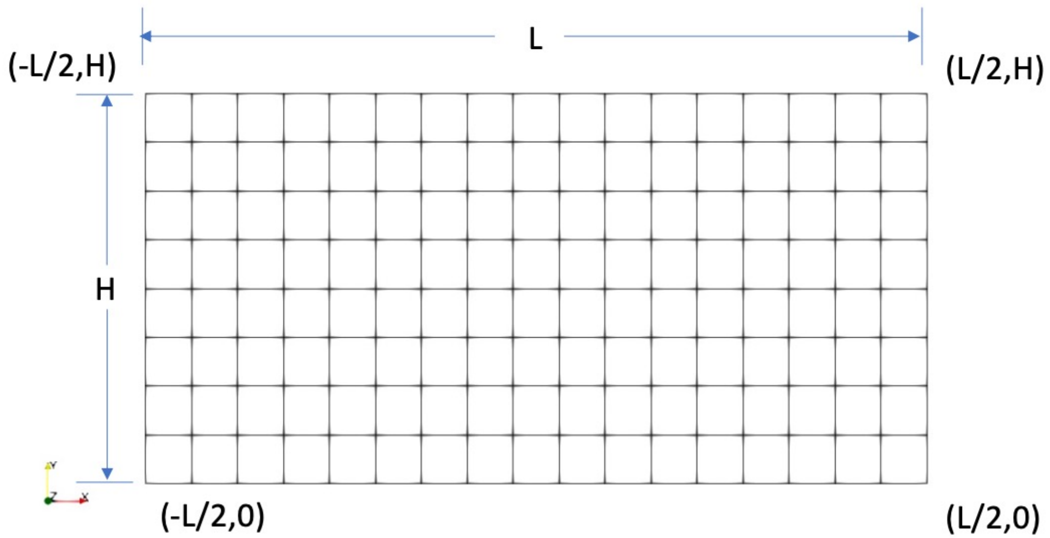


Figure 1: Two-dimensional couette flow in which the height is 2 m and length, 1 m

Nalu/reg_tests/test_files/laboratory/2d_quad9_couette: Equations

- Subject to the imposed conditions, the momentum equation reduces to:

$$\mu \frac{d^2 u_x}{dy^2} = 0$$

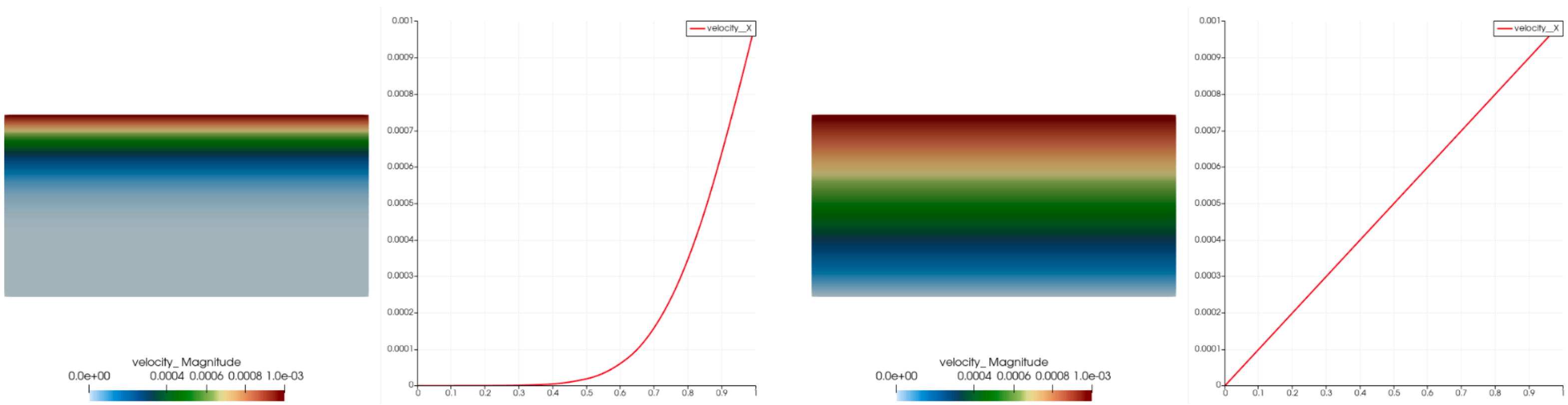
- With analytical solutions (at a given Reynolds number): $Re = \frac{\rho u_b H}{\mu}$

$$u_x(y) = k_1 y + k_2 \qquad u_x(y) = \frac{u_b}{H} y$$

- Simple, and a linear profile

Nalu/reg_tests/test_files/laboratory/2d_quad9_couette: Simulation Results

- Start-up adds additional complexity to the solution, however, at steady state, our profile is predicted to be linear



(a) (b)

Figure 2: Velocity shadings (left) and velocity profile (right) for the $Re = 1236$ case.

Nalu/reg_tests/test_files/laboratory/2d_quad4_channel: Geometry/Boundary Conditions

- Top and bottom, no-slip wall
- Left and right sides, either open (specified pressure drop) or with a body force, periodic

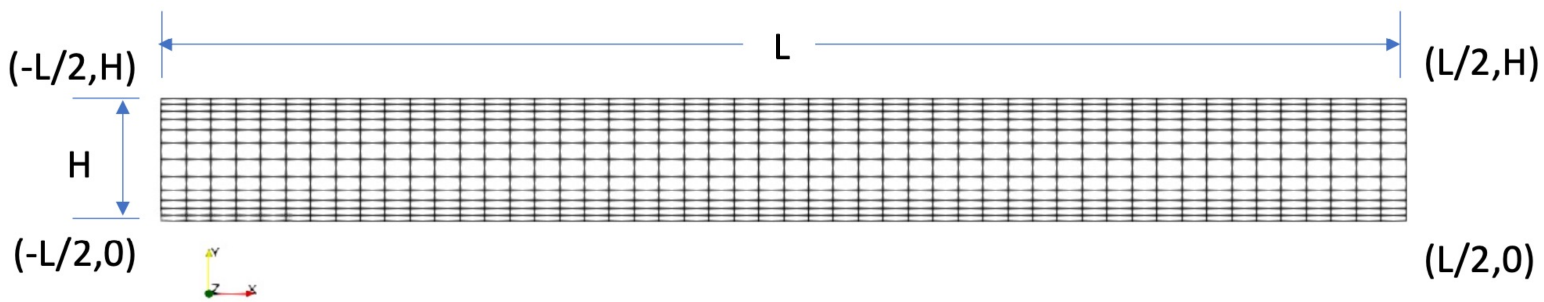


Figure 1: Two-dimensional channel flow in which the height is unity and length, 10.

Nalu/reg_tests/test_files/laboratory/2d_quad4_channel: Equations

- Subject to the imposed conditions, the momentum equation reduces to:

$$\mu \frac{du_x^2}{dx^2} = \frac{dP}{dx}$$

- With analytical solutions (at a given Reynolds number): $Re_\tau = \frac{\rho u_\tau H/2}{\mu}$

$$u_x(y) = \frac{1}{\mu}\frac{dP}{dx}\frac{y^2}{2} + k_1 y + k_2 \qquad u_x(y) = \frac{1}{2\mu}\frac{dP}{dx}\left[y^2 - Hy\right] \qquad u_x^{max} = \frac{1}{8\mu}\frac{dP}{dx}H^2$$

- Quadratic profile
- Wall shear stress and pressure gradient balance:

$$\int \frac{dP}{dx} dV = \int \tau_w dA$$

Nalu/reg_tests/test_files/laboratory/2d_quad4_channel: Sizing

- Let's run at Re_τ=10

Reynolds number:

- Ratio of inertial to viscous forces

$$Re_D = \frac{\rho u D}{\mu}$$

- In this channel, define Reynolds number based on the wall friction velocity, u_τ (at H/2 length scale)

$$Re_\tau = \frac{\rho u_\tau H/2}{\mu}$$

Let us test a simulation in which the Reynolds number based on wall friction velocity, u^τ, and half-channel height $H/2$, is ten: $Re^\tau = 10$. By constraining the Reynolds number, wall friction velocity, and density, the consistent viscosity is obtained via,

$$\mu = \frac{\rho u^\tau H}{2Re^\tau}. \tag{8}$$

To obtain the required pressure gradient, we exercise the relationship,

$$u^\tau = \sqrt{\frac{\tau_w}{\rho}}, \tag{9}$$

along with global momentum balance,

$$\int \frac{dP}{dx} dV = \int \tau_w dA, \tag{10}$$

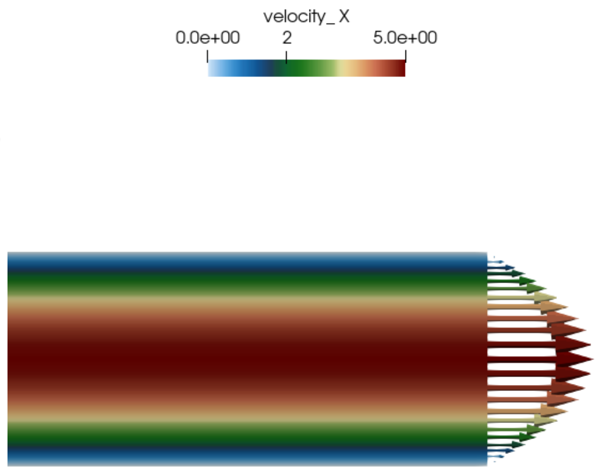
with $dV = LH$ and $dA = 2L$, to obtain the relationship between required pressure gradient and wall shear stress, $\frac{dP}{dx} = 2\tau_w$.

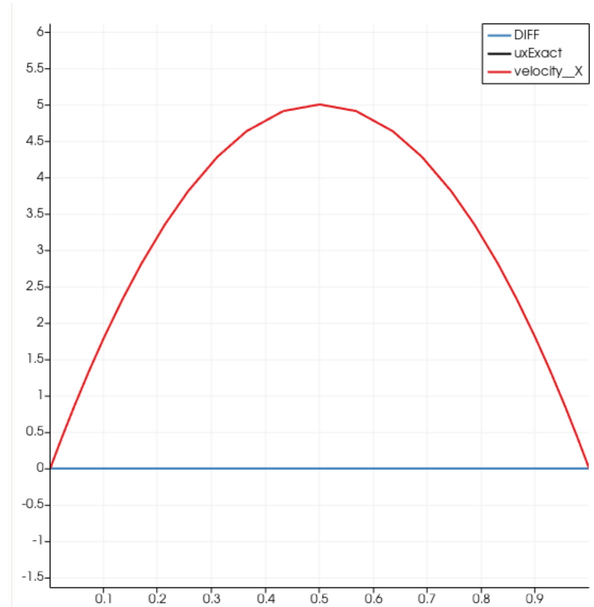
Nalu/reg_tests/test_files/laboratory/2d_quad4_channel: Simulation Results

Analytical Expression:

$$u_x(y) = \frac{1}{2\mu}\frac{dP}{dx}\left[y^2 - Hy\right].$$

- Zero Error when evaluating the norm at the nodes (in general, we may integrate over a domain and choose integration points that are not *nodally-lumped*
- However, the post-processed wall shear stress showcases error…





Nalu/reg_tests/test_files/laboratory/3d_tet4_pipe: Geometry/Boundary Conditions

- No-slip (walls) outer pipe
- Periodic (left and right) with a constant body force …or… Open (left and right pressure drop)

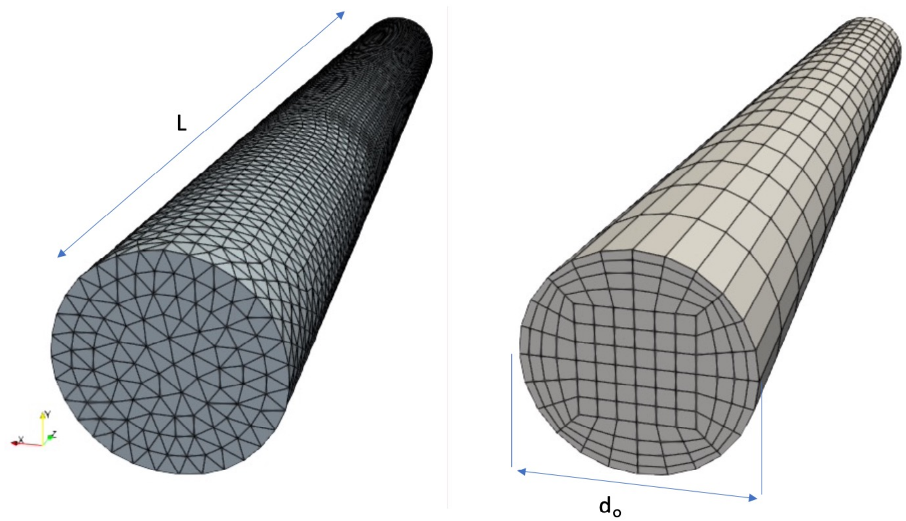


Figure 1: Three-dimensional pipe flow configuration of length L and diameter d_o outlining the Tet4 (left) and Hex8 (right) topology.

Nalu/reg_tests/test_files/laboratory/ 3d_tet4_pipe: Equations

- Subject to the imposed conditions, the axial momentum equation (cylindrical coordinates) reduces to:

$$\frac{dP}{dz} = \frac{1}{r}\frac{\partial r \tau_{\tau_{rz}}}{\partial r} \qquad \frac{\partial u_z}{\partial r}\Big|_{r=0} = 0 \qquad u_z\big|_{r=R} = 0$$

- With analytical solutions (at a given Reynolds number): $Re_\tau = \dfrac{\rho u_\tau D}{\mu}$

$$\frac{r^2}{2}\frac{dP}{dz} = r\mu\frac{\partial u_z}{\partial r} + k_1 \qquad u_z(r) = \frac{1}{4\mu}\frac{dP}{dz}\left[r^2 - R^2\right] \qquad u_x^{max} = -\frac{R^2}{4\mu}\frac{dP}{dZ}$$

- Quadratic profile
- Wall shear stress, and pressure gradient balance

$$\int \frac{dP}{dz} dV = \int \tau_w dA$$

Nalu/reg_tests/test_files/laboratory/ 3d_tet4_pipe: Sizing

- Let's run at Re_τ=20

Reynolds number:

- Ratio of inertial to viscous forces

$$Re_D = \frac{\rho u D}{\mu}$$

- In this channel, define Reynolds number based on the wall friction velocity, u_τ (at d_o length scale)

$$Re_\tau = \frac{\rho u_\tau d_o}{\mu}$$

Let us test a simulation in which the Reynolds number based on wall friction velocity, u^τ, and diameter of the pipe (0.02 m) is $Re^\tau = 20$. In this mesh configuration, the length L is 0.2 m. By constraining the Reynolds number, wall friction velocity, and density, the consistent viscosity is obtained via,

$$\mu = \frac{\rho u^\tau d_o}{Re^\tau}. \quad (16)$$

To obtain the required pressure gradient, we exercise the relationship,

$$u^\tau = \sqrt{\frac{\tau_w}{\rho}}, \quad (17)$$

along with global momentum balance,

$$\int \frac{dP}{dz} dV = \int \tau_w dA, \quad (18)$$

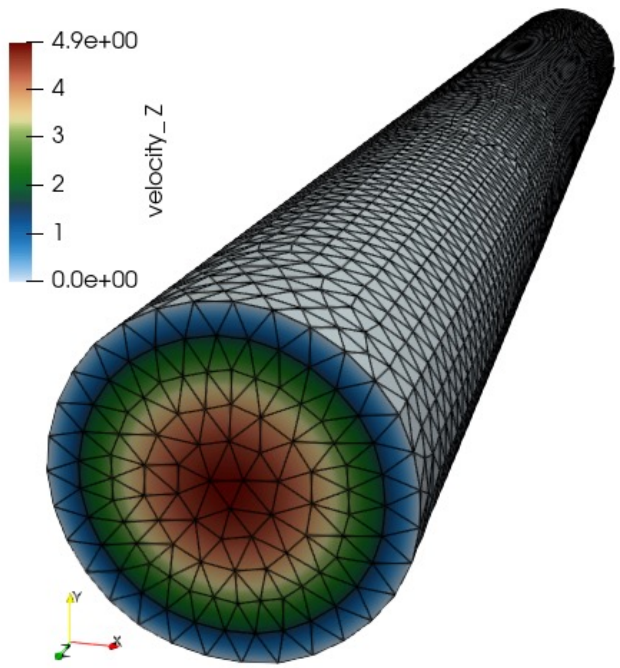
with $dV = \pi r^2 L$ and $dA = 2\pi r L$, to obtain the relationship between required pressure gradient and wall shear stress, $\frac{dP}{dz} = 2\frac{\tau_w}{r}$.

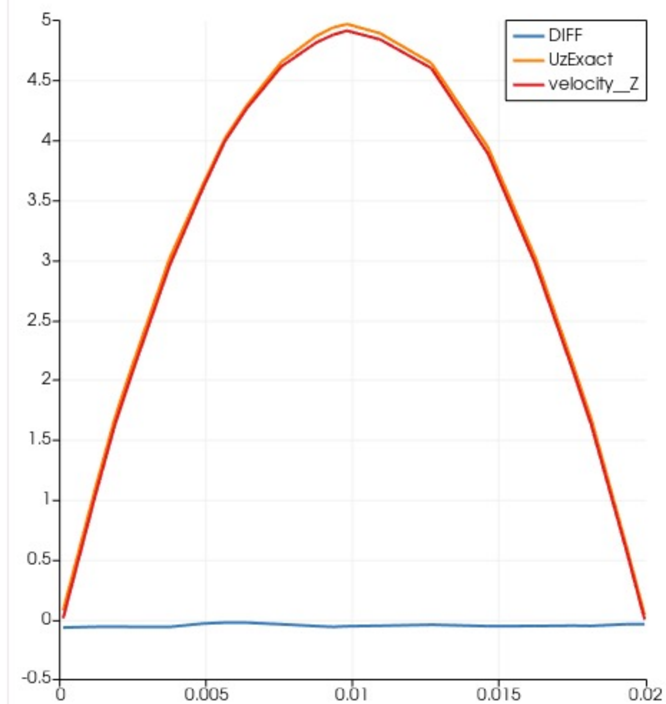
Nalu/reg_tests/test_files/laboratory/2d_quad9_channel: Simulation Results

Analytical Expression:

$$u_z(r) = \frac{1}{4\mu}\frac{dP}{dz}\left[r^2 - R^2\right].$$

Non-zero error when evaluating the norm at the nodes...

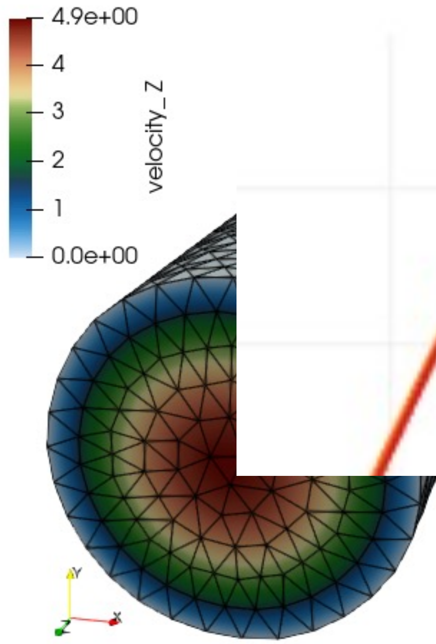


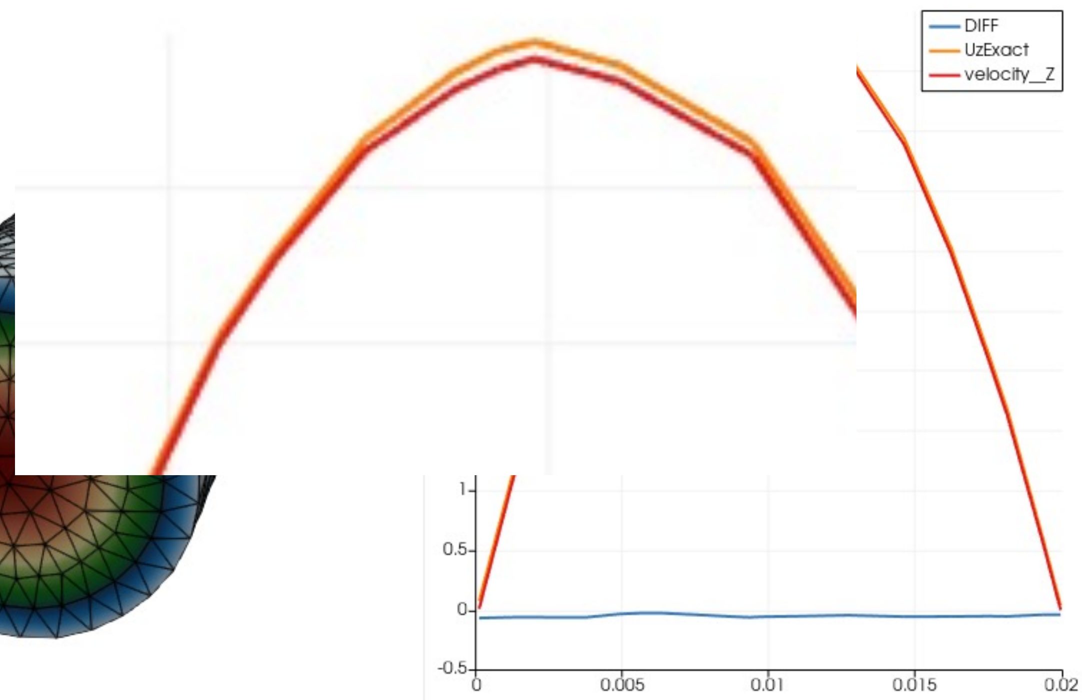


Nalu/reg_tests/test_files/laboratory/2d_quad9_channel: Simulation Results

Analytical Expression:

$$u_z(r) = \frac{1}{4\mu}\frac{dP}{dz}\left[r^2 - R^2\right].$$

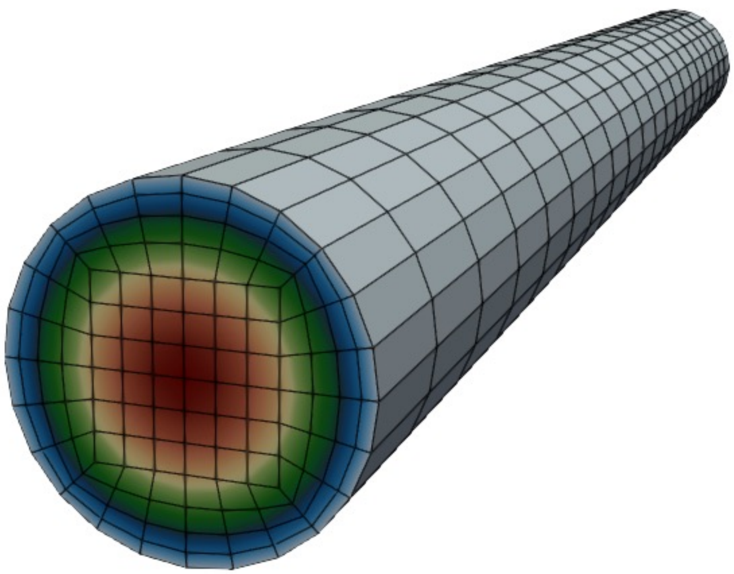


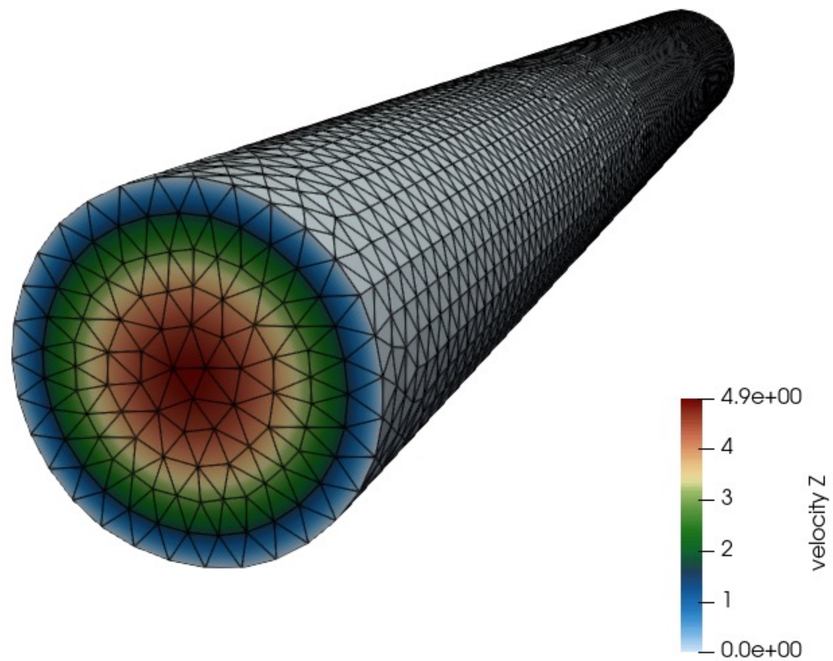


Non-zero error when evaluating the norm at the nodes…

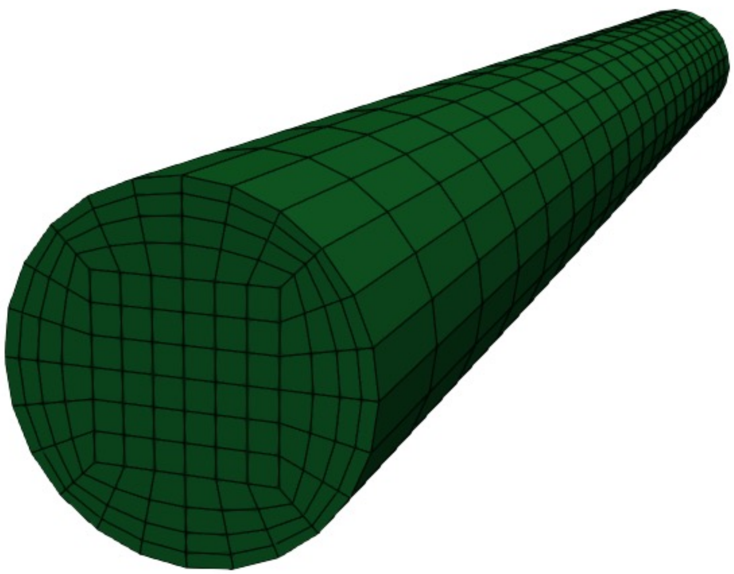
What happened?

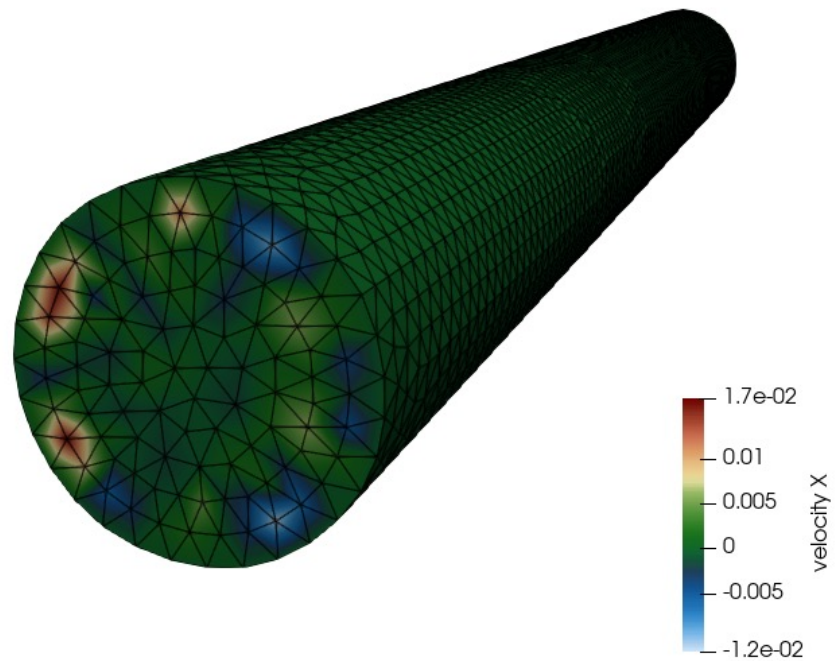
Nalu/reg_tests/test_files/laboratory/2d_quad9_channel: What About Tet4 vs Hex8?





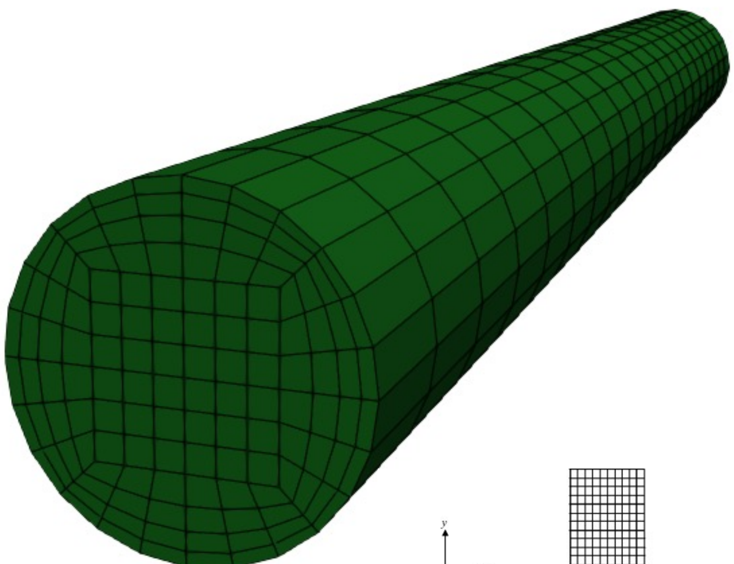
Nalu/reg_tests/test_files/laboratory/2d_quad9_channel: What About Tet4 vs Hex8?

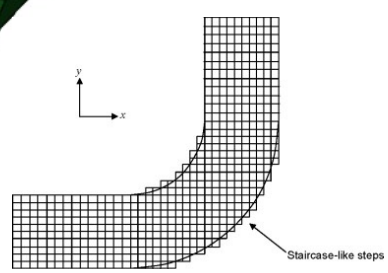


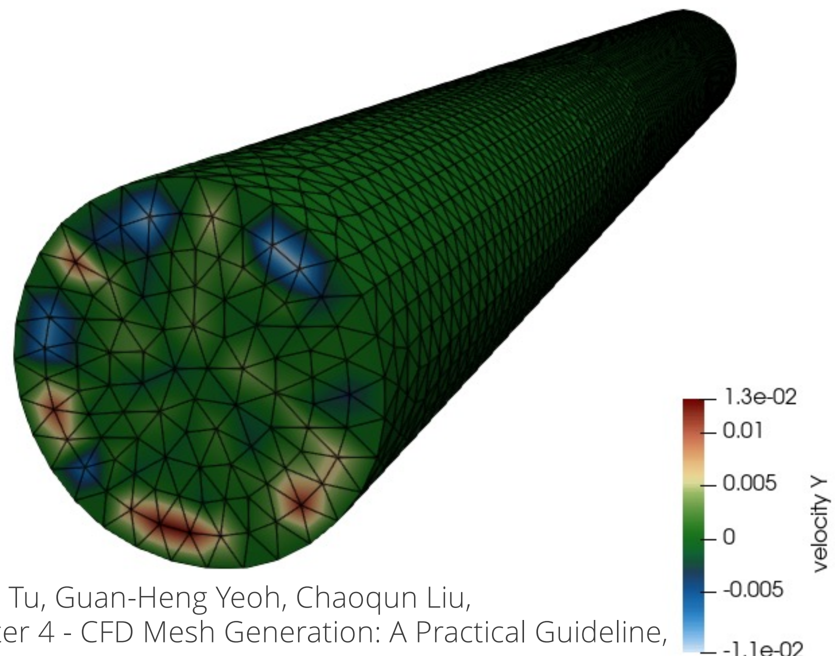


~0.3% error in non-streamwise velocity components in the tet-based result, ~0% for Hex8!!!

Nalu/reg_tests/test_files/laboratory/2d_quad9_channel: What About Tet4 vs Hex8?







Jiyuan Tu, Guan-Heng Yeoh, Chaoqun Liu,
Chapter 4 - CFD Mesh Generation: A Practical Guideline,
Editor(s): Jiyuan Tu, Guan-Heng Yeoh, Chaoqun Liu,
Computational Fluid Dynamics (Third Edition),
Butterworth-Heinemann, 2018, Pages 125-154,

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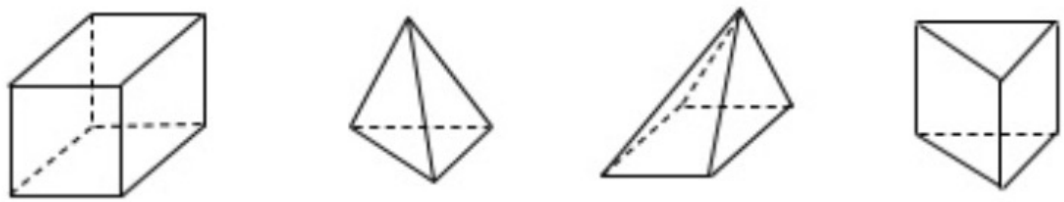
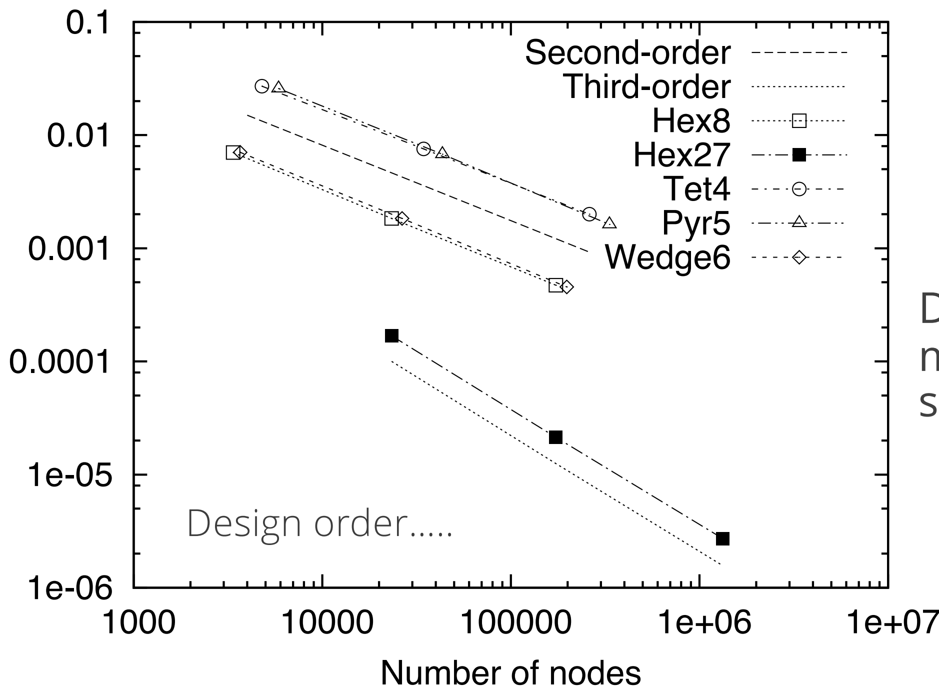
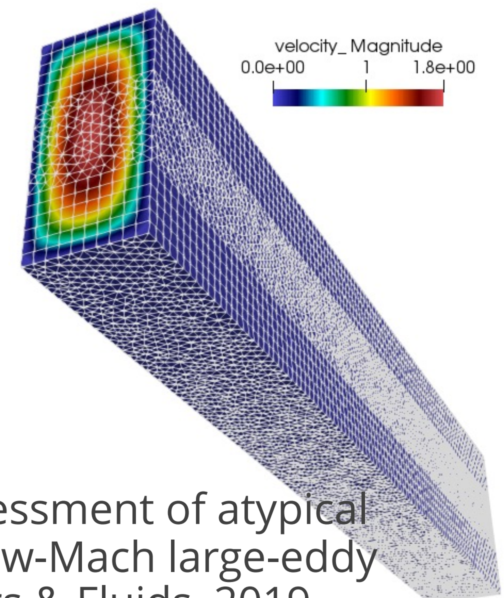
Unstructured Mesh Types (Review) and Results

Hex8 Tet4 Pyramid5 Wedge6







Domino et al., “An assessment of atypical mesh topologies for low-Mach large-eddy simulation”, Computers & Fluids, 2019

$$u_z = -\frac{1}{2\mu}\frac{dp}{dz}\left[b^2 - y^2 - \frac{4}{b}\sum_{n=0}^{\infty}(-1)^n \frac{1}{m^3}\frac{cos(my)cosh(mx)}{cosh(ma)}\right]$$

Conclusions

- Geometric fidelity for curved surfaces can be very important
- Unstructured meshing generally affords easier meshing, with increase throughput (especially when simulating complex geometries)
- Hex-based errors may be lower than Tet-based simulation results, however, balanced with ease of meshing
- The key is that all methods are “design-order”, i.e., demonstrate expected reduction of errors as a function of mesh size